WBG-Based High Output Power Electronics

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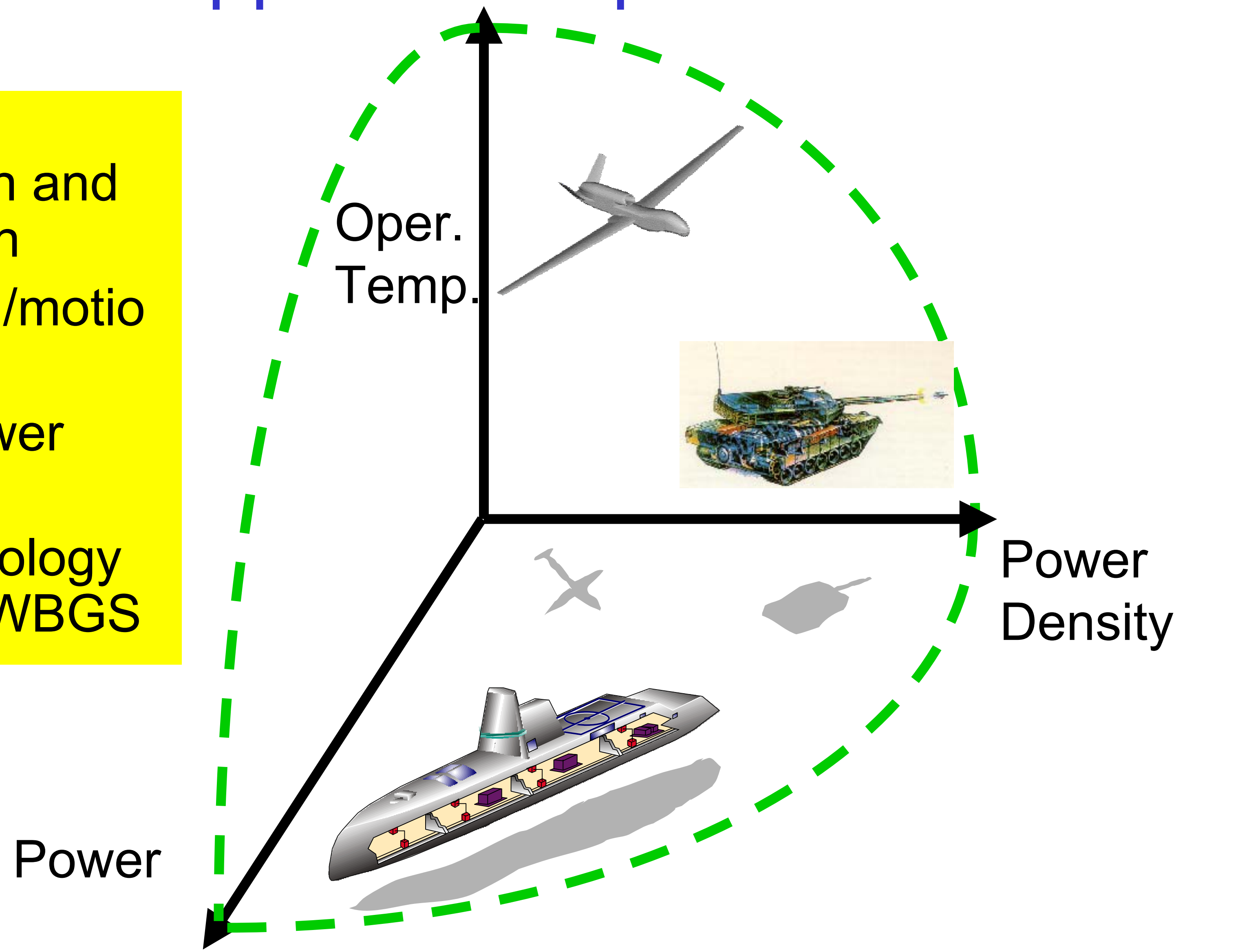
Outline

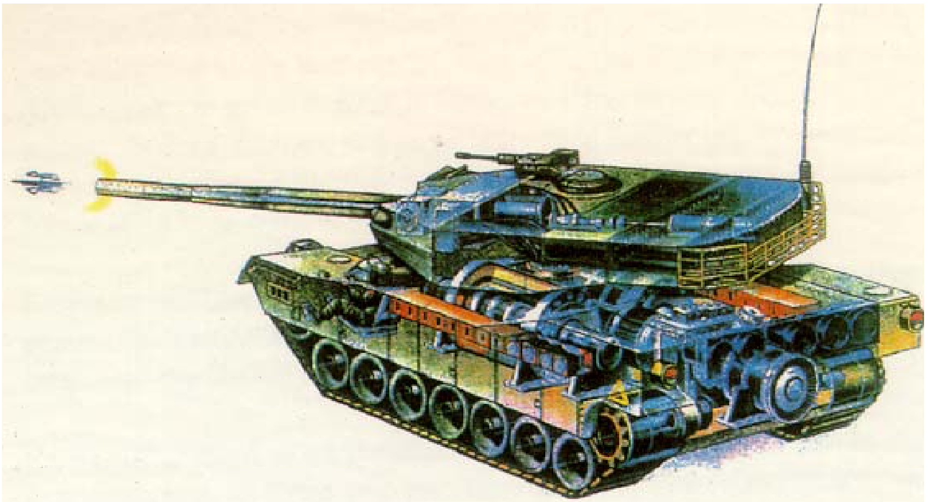
- Applications/needs for high output power electronics
- High Power Solid-State Electronics Program Goals and Accomplishments
  - FY97 – FY00
  - Managed by E.R. Brown then D.J. Radack
- WBG Technology Opportunities for advanced power applications

High Output Power Electronics Application Space

- Power Distribution and Conversion
- Propulsion/motio n control
- Pulse Power Switching
- One technology solution - WBGS



Electric Combat Vehicle



Needs to be light!

Active armor

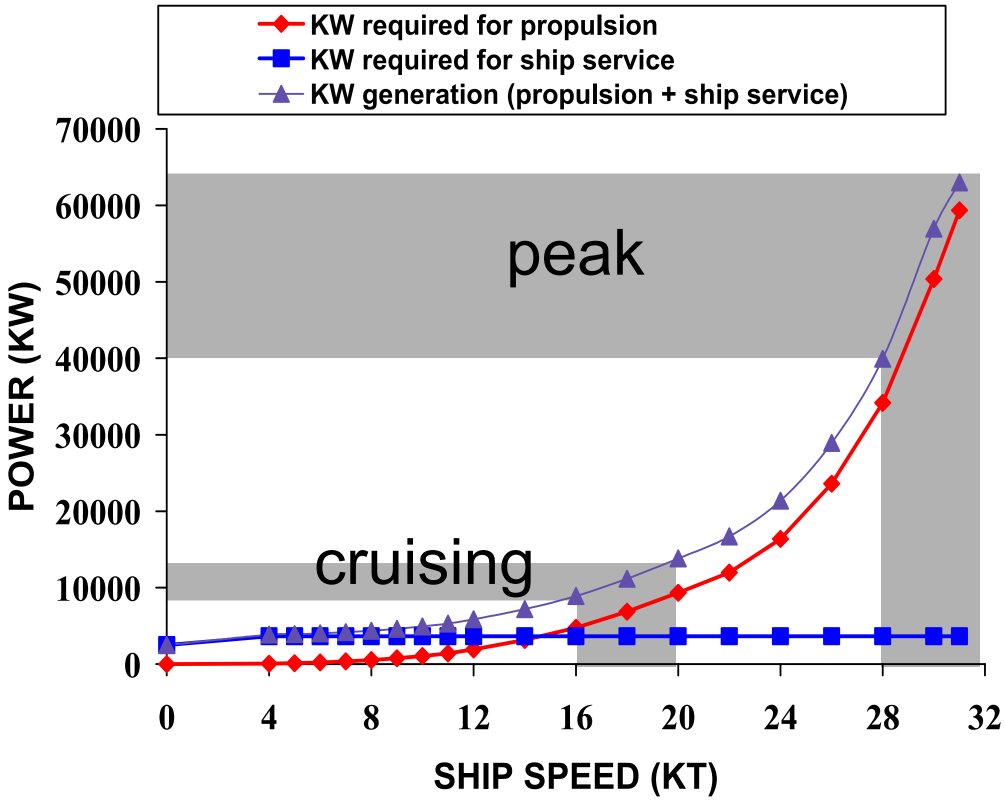
Active suspension

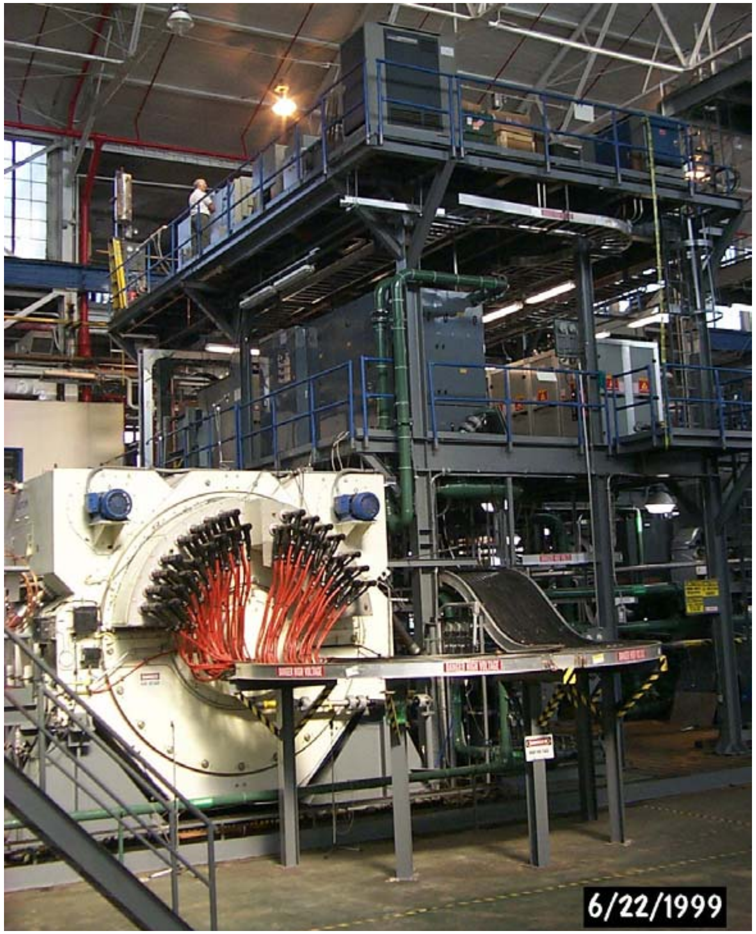
EM Weapons

Energy efficiency

- Traction motor controller: >300kW, >2kV, >750A rms, >25kHz, 150 degrees C
- EM weapons: >200kJ energy, 40kV, di/dt > 10kA/us, 100kHz, low losses
- HP Inverter: 10MW for 0.1-0.5s, 10kV, 3kA, 25kHz, compact size

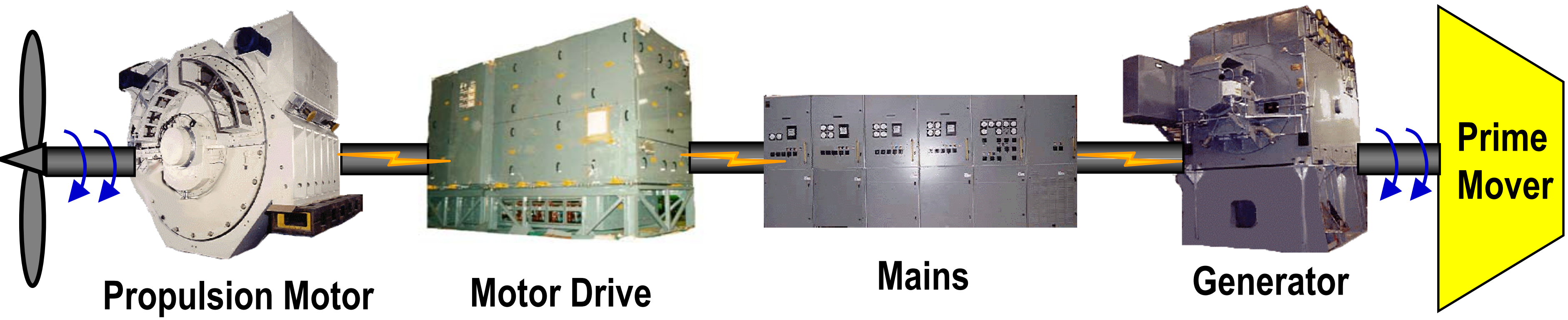
Ship Power Application

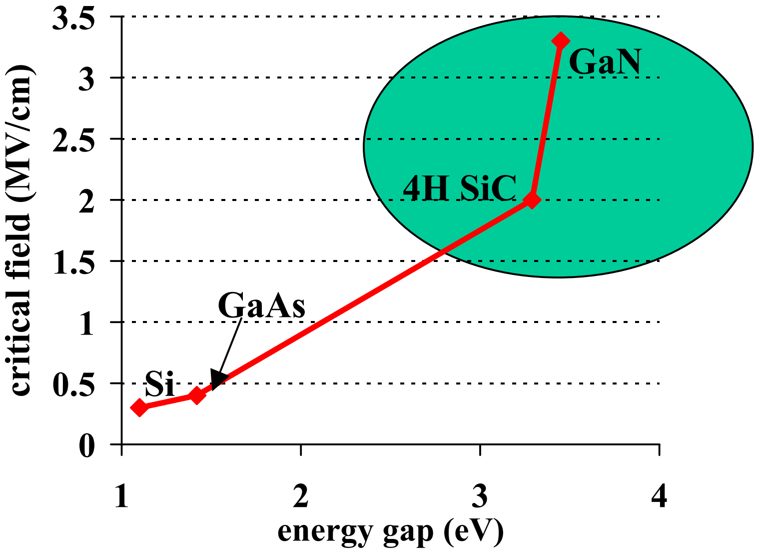


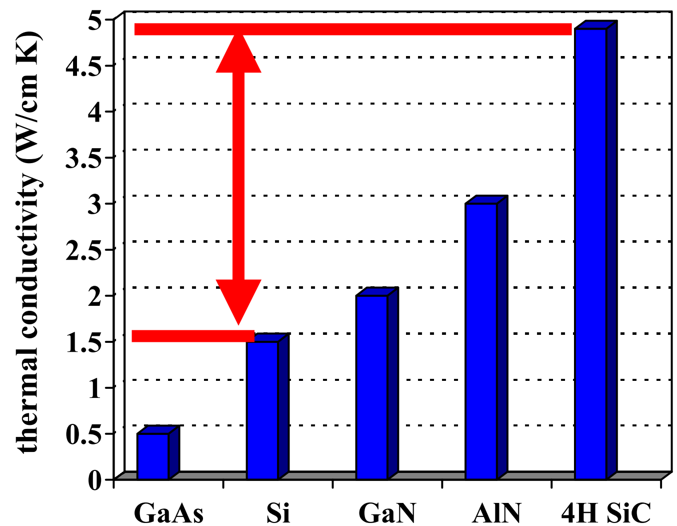


Motor Controller is key – SiC will increase performance and efficiency with smaller size

Power Electronics for Motors







Motor performance depends on drive electronics – SiC power devices will enable high performance motor drives

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  - FY97 – FY00, joint with EPRI
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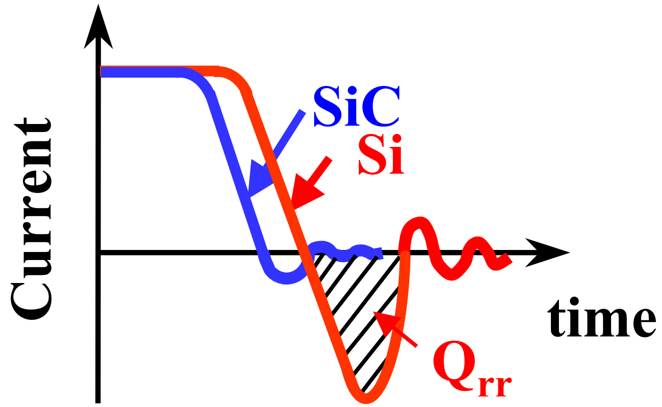
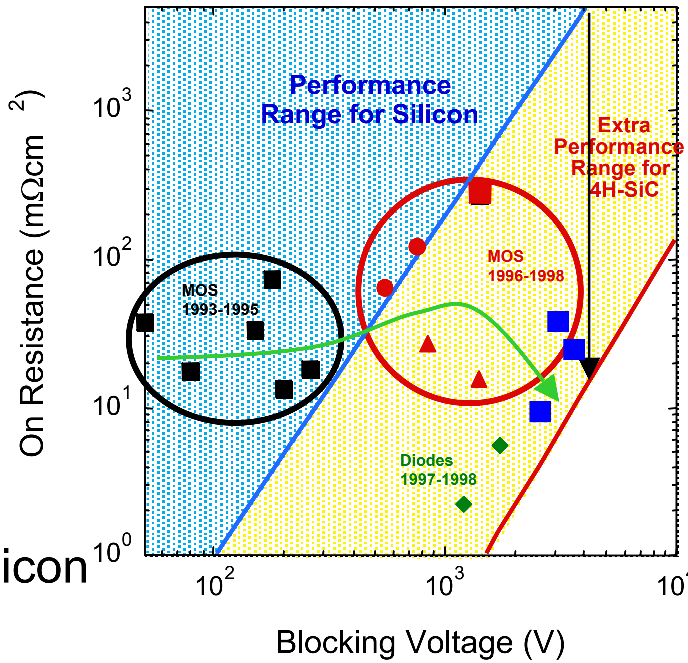
Silicon Carbide Power Electronics





(1) ~8X higher breakdown electric field than Silicon

(2) 3X higher thermal conductivity and larger band gap energy than Si

(3) 10X faster switching speed over Si, near zero reverse recovery

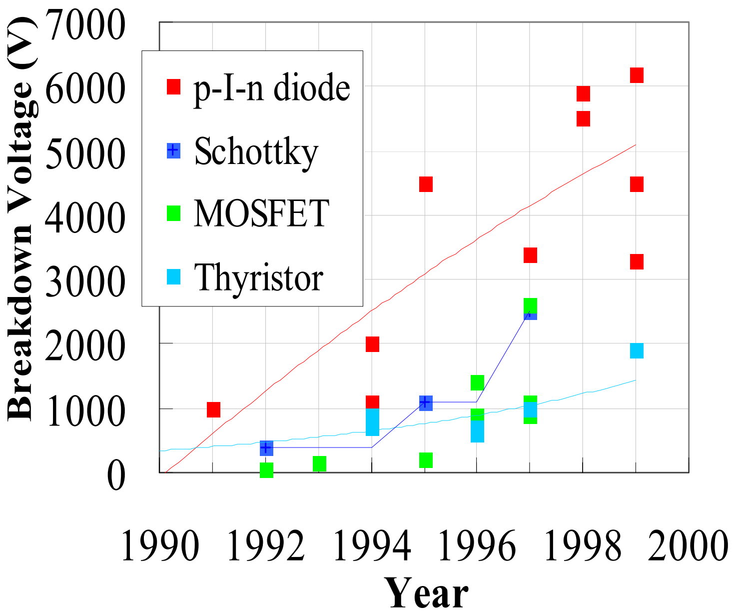
(4) 10-50X reduction in complete HV circuit

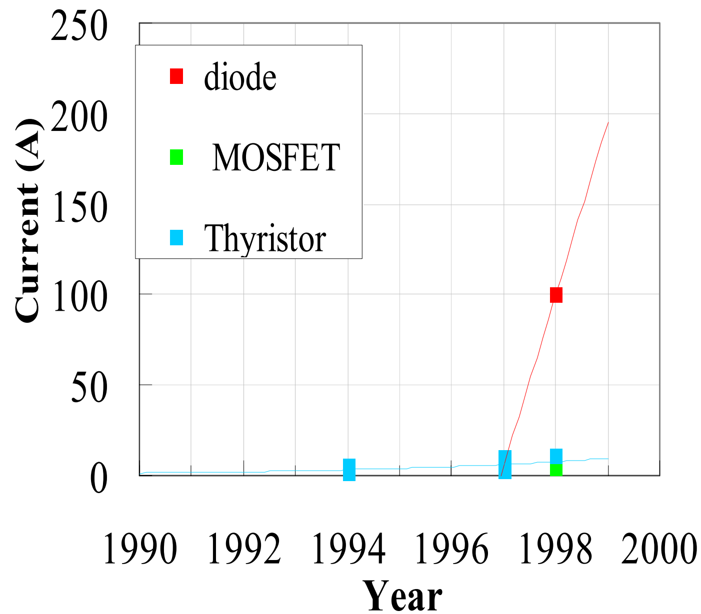
Silicon Carbide material properties a match for high power electronics – bulk electronic materials now available!

High Power Solid-State Program Accomplishments

- Program Duration: FY97-00, \$30M (\$12M cost share from EPRI)
  - Industry, academia, gov't participation in program
  - Project summaries and program participant final briefings are on MTO web site in the "High Power Solid-State Electronics" Archives
  - TTO CHPS App., DSO SiC materials and AF Title 3
- Developed and transferred high yield unit process technologies for SiC power devices (diodes and thyristors)
  - epitaxial layer growth, doping, contacts, oxides
- Demonstrated feasibility of fabricating SiC high power electronic devices in industrial fabrication lines (diodes, FETs, thyristors)
- Demonstrated assembly and packaging technology for 1kW/cm^2 SiC power devices first ever all SiC electronic assemblies
  - Fabricated die for TTO CHPS

Progress in SiC Power Electronics

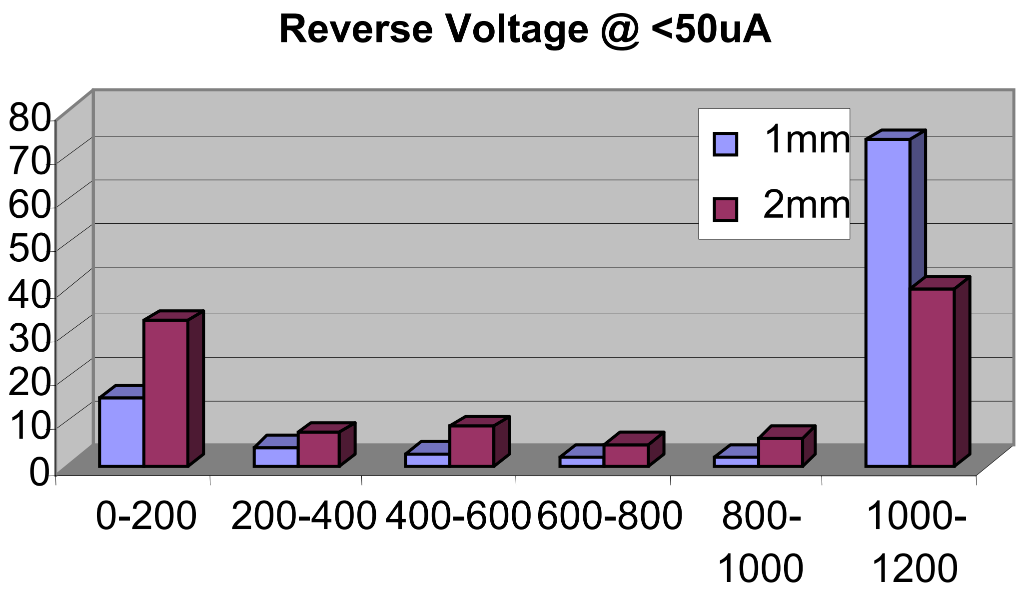




<u>Selected SiC Device Accomplishments (FY00):</u>

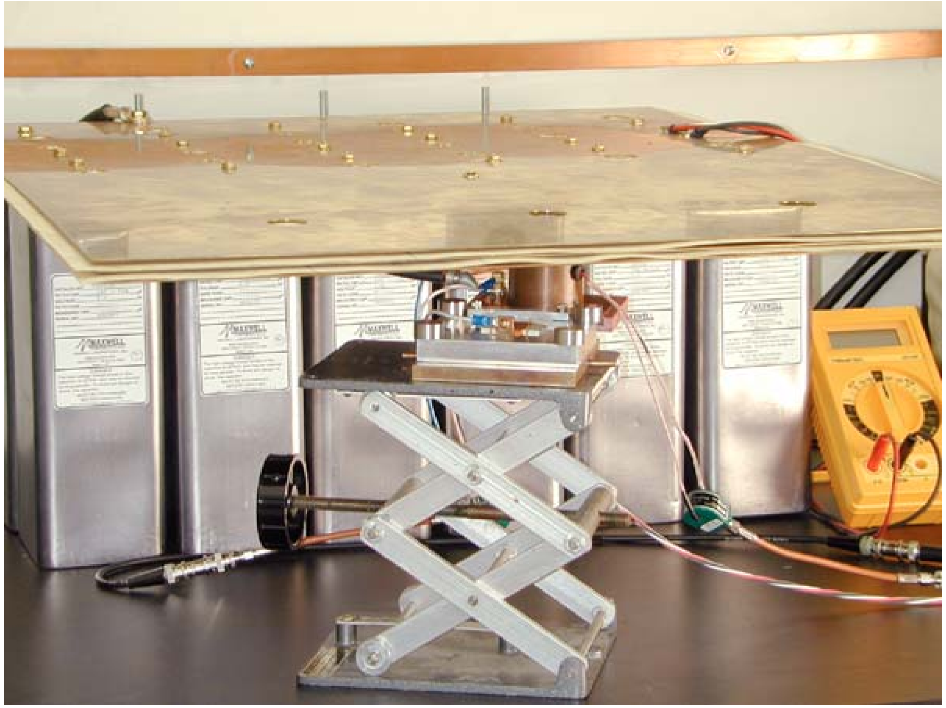
– 6 kV diodes
– Yielded hundreds of >5kV diodes
– >100 A diode assembly
– 3 kV GTOs
– 69 A conduction / 11 A turn-off GTOs

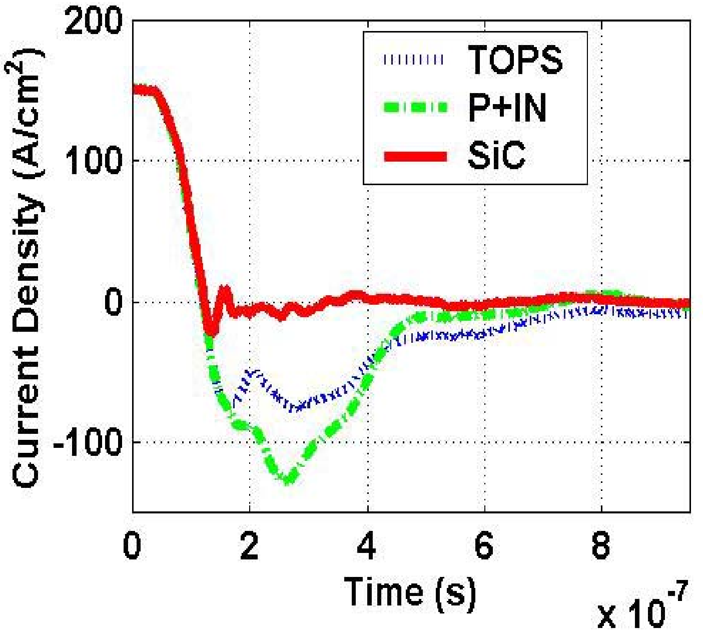
HP Diodes Show >70% Yield

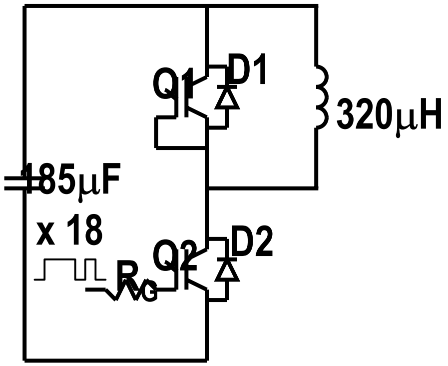


-Strong dependence on epi quality
-Reasonable (40%) yields even at 2 mm

High Power Testing

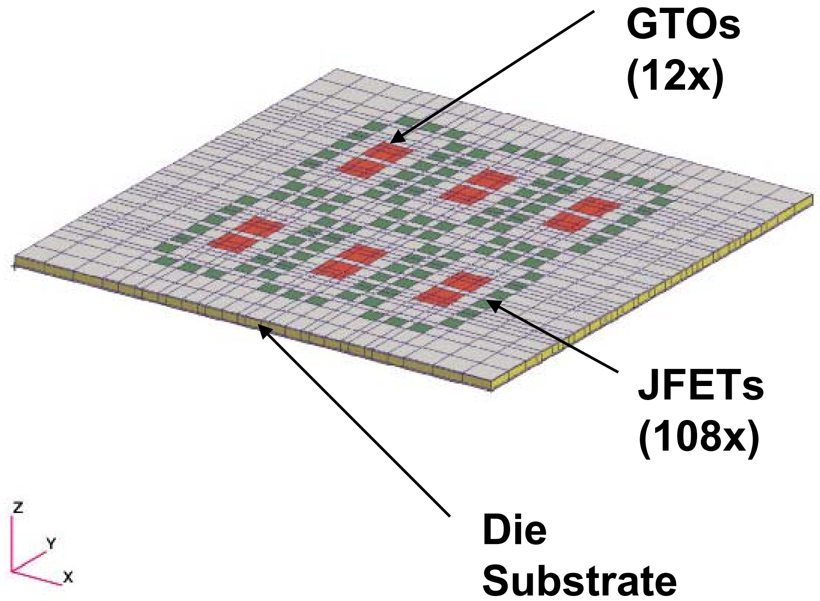






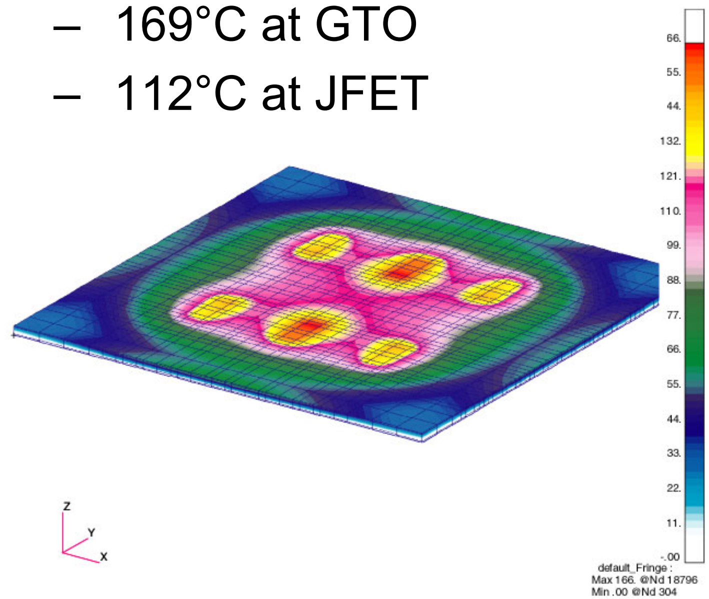
Minimal Diode Reverse Recovery Charge!!!

Electrothermal Modeling



<u>Circumferential Cooling</u>

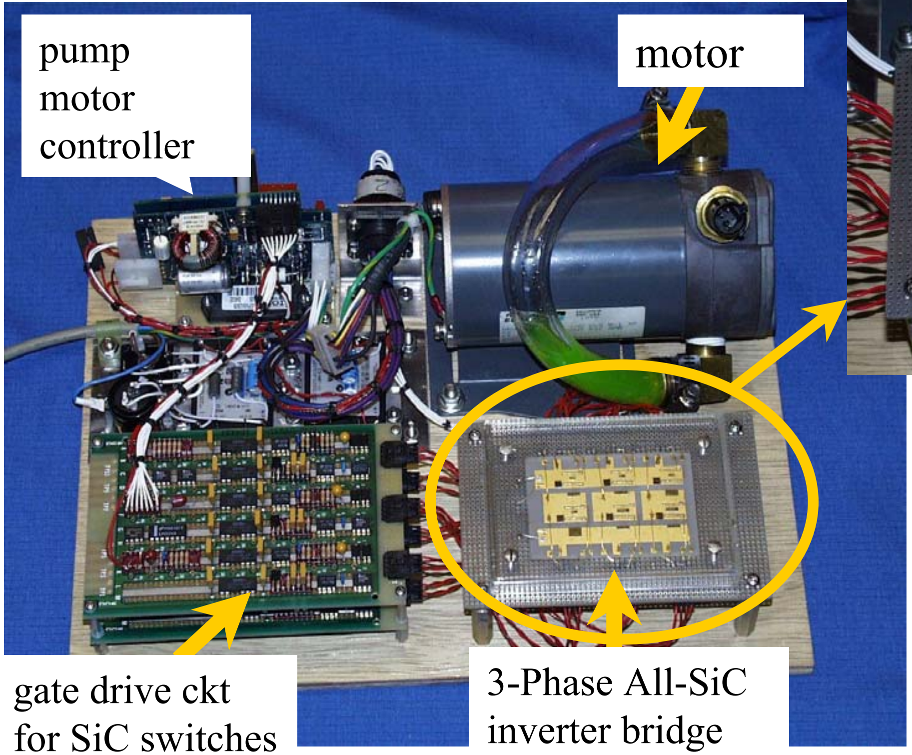
- Circum cooling with CuW Encapsulated pyrolytic graphite
- Maximum Temperature
  - 169°C at GTO
  - 112°C at JFET

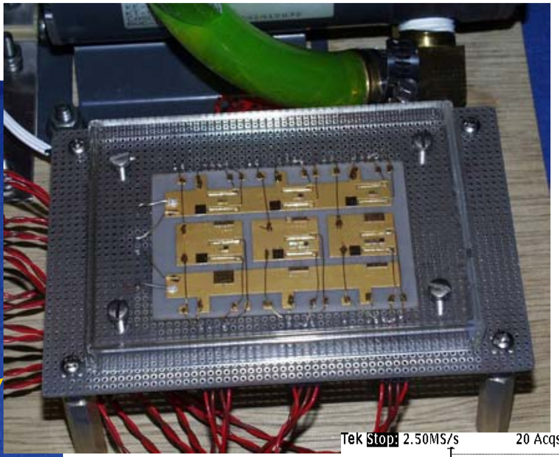


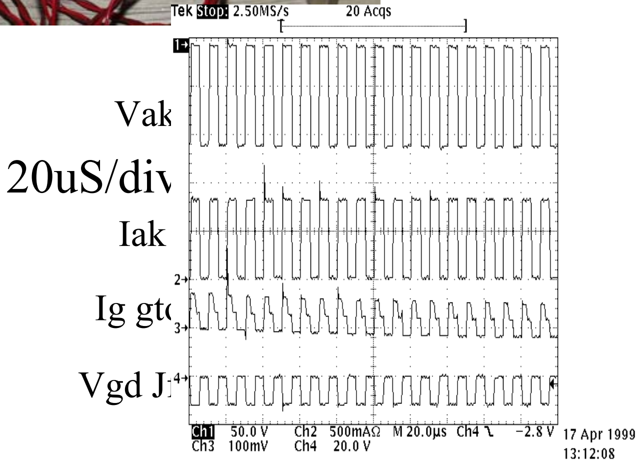
Completed Coupled Electrothermal Models for SiC Devices, Excellent Agreement to Experimental Data

First Operational All SiC Motor Drive

1kW, 3-phase PWM motor drive controller







SiC Microinverter operating at 100kHz, 100V, 0.75 amp confirms SiC promise and models

MTO SiC Devices Used For First Ever Demo of all-SiC Power Electronics Circuit

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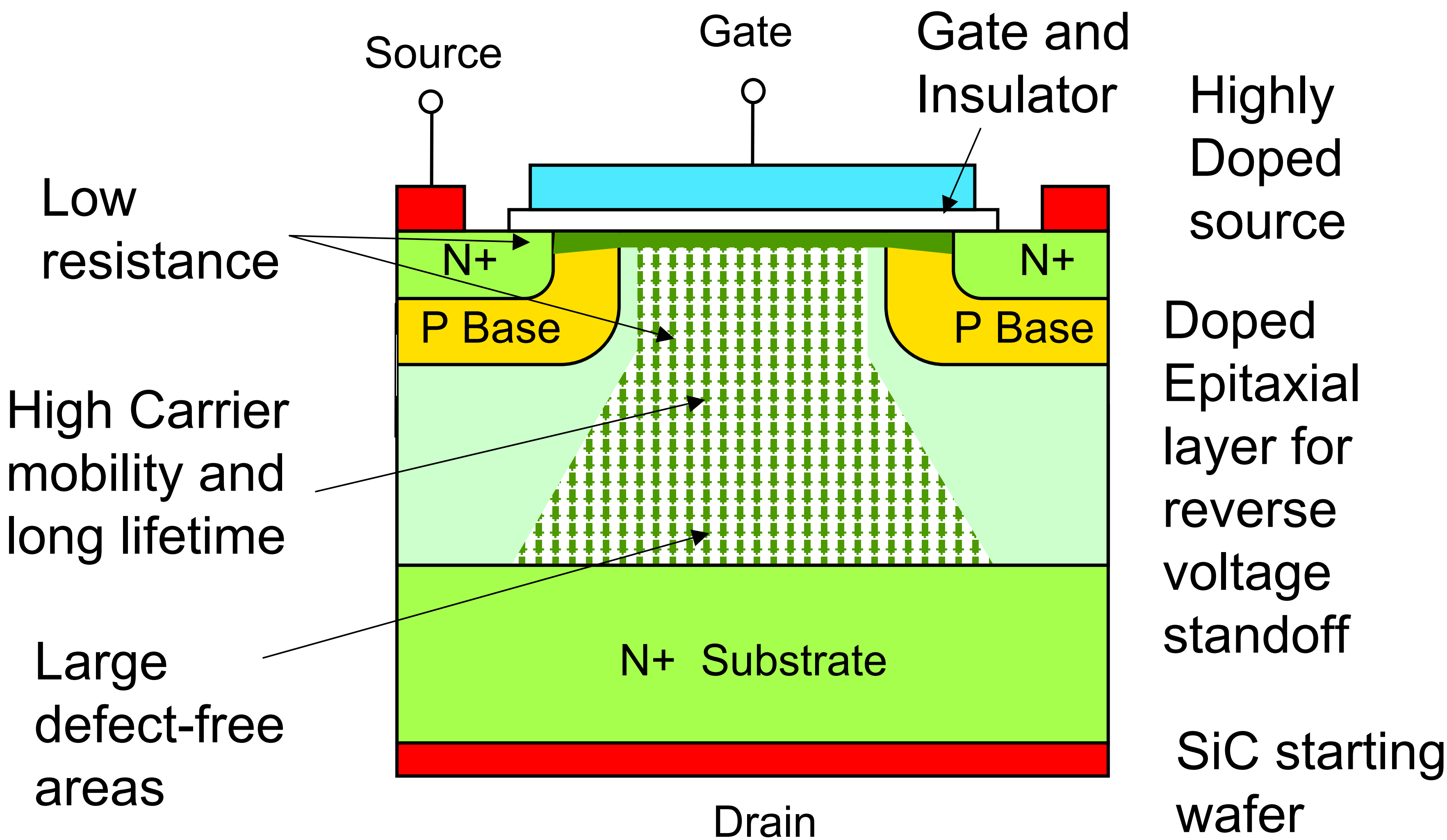
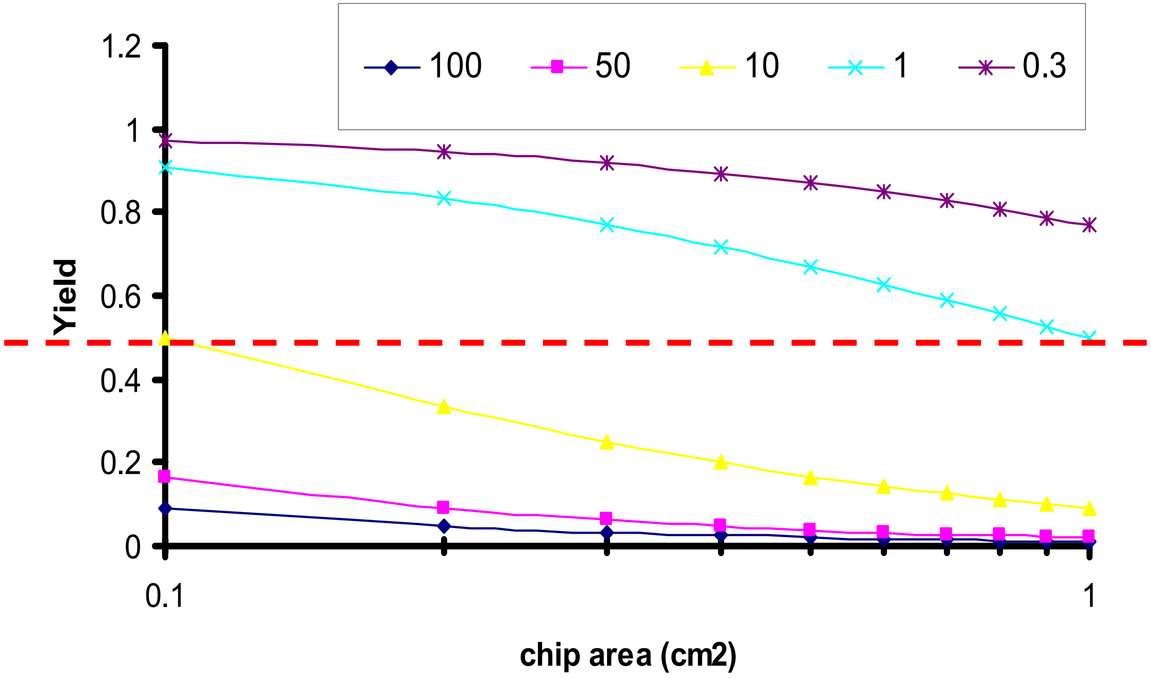
  - Increase chip area
  - MOS structures

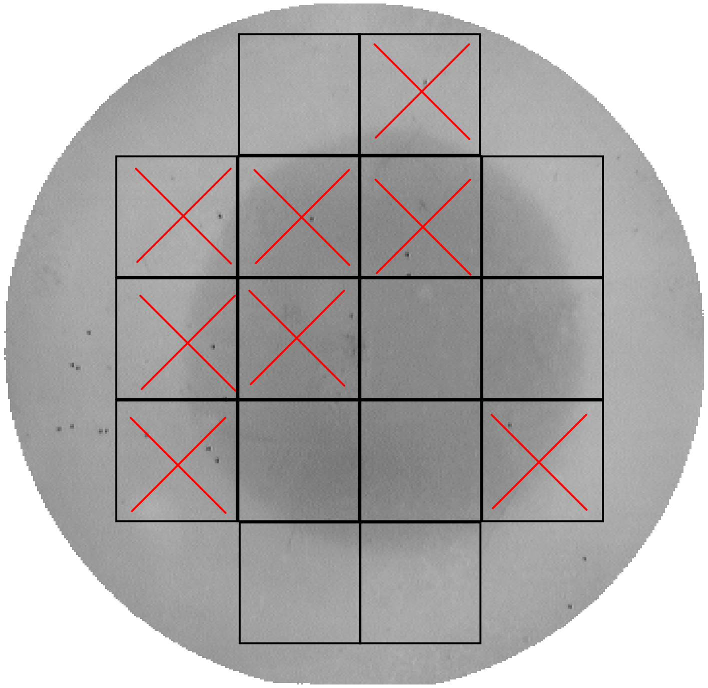
SiC Electronic Materials for Power



4H SiC is best overall choice for high voltage and current

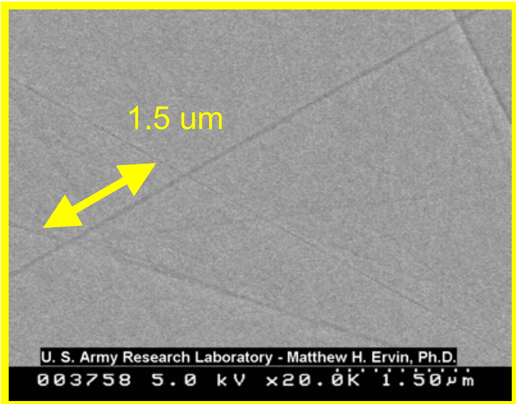
New Direction: Increase Usable Chip Area for High Power Devices





Defect free Cm^2 area chips necessary for yielding high current, high voltage devices

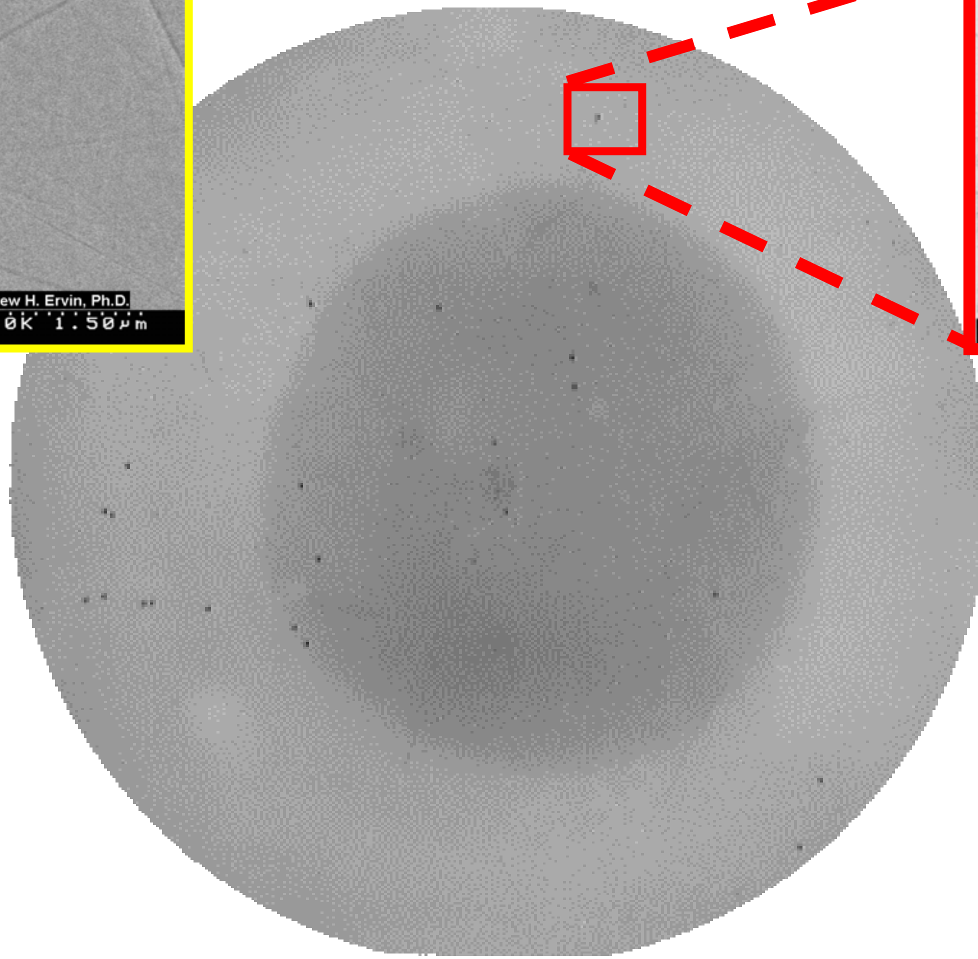
Material Issues for High Power

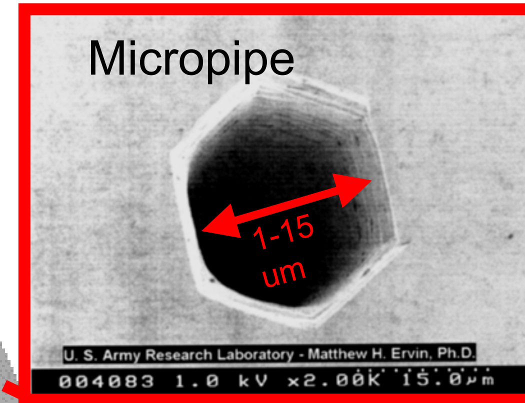


Surface Defects:

-Eliminate

-Mitigate





Wafer Defects:

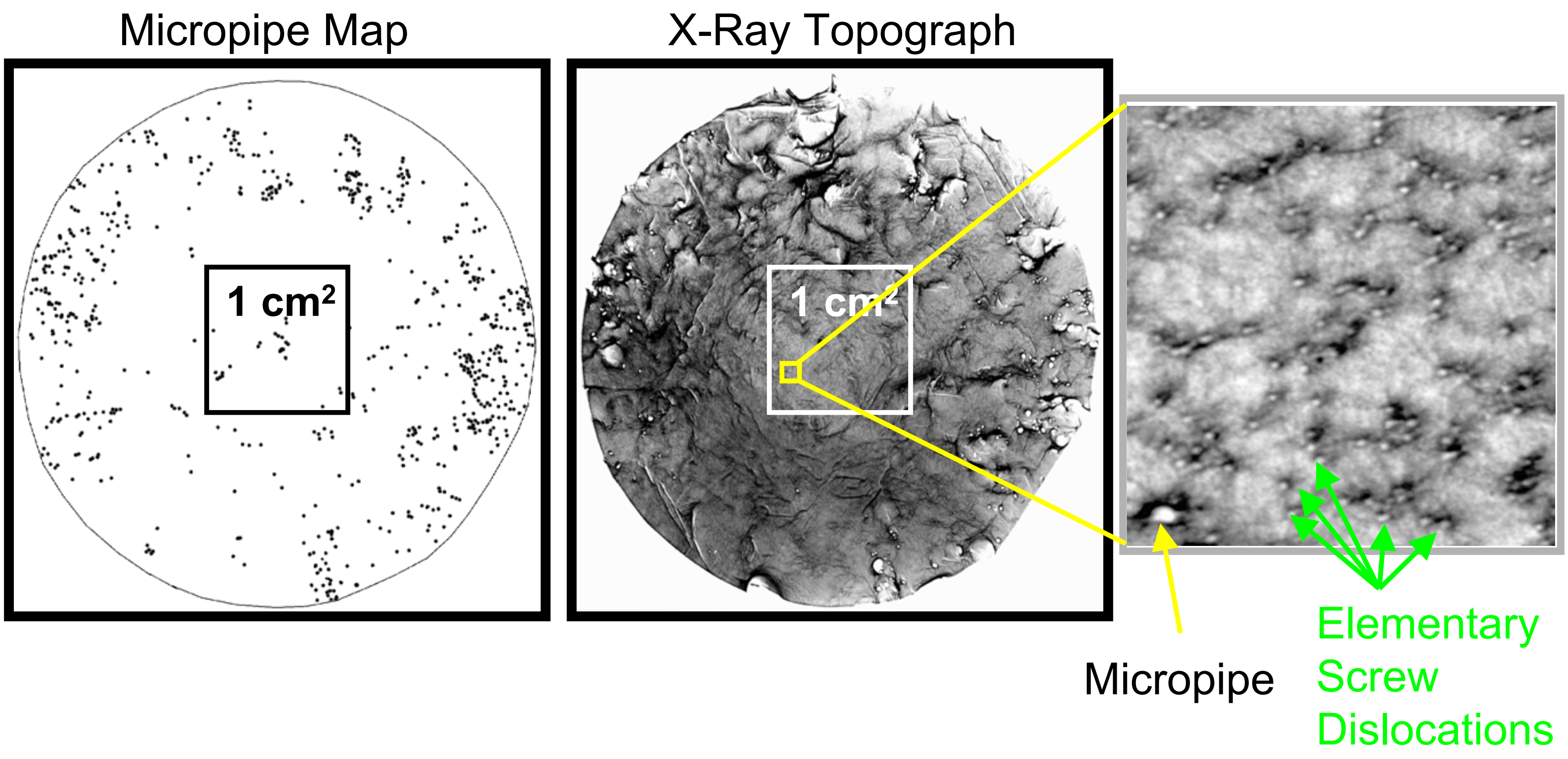
-Eliminate

-Cover

-Fill

Challenges: Large Defect Free Areas (cm^2) for HP Devices

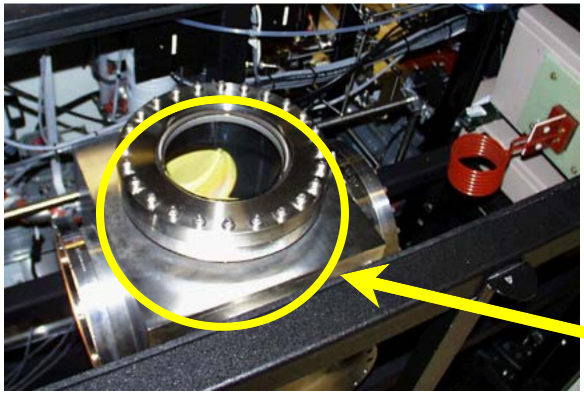
SiC Wafer Defects



Total Defect Density >> Micropipe Density

High Temperature SiC CVD for WBG Epi

Need ~ **<u>500 µm</u>** (@1 x 10^{14} cm^{-3}) Epi Layer for 25 kV blocking voltage.

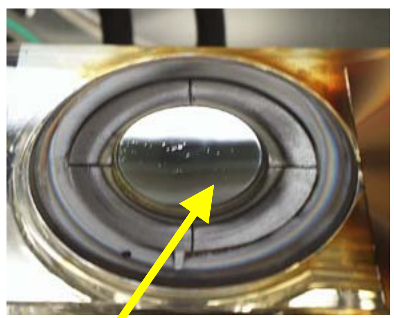


Current Epi Growth Rate Limitations:

- CVD Temp up to 1600°C
- growth rates ~ 3.5 µm/h
- 500 µm in >140 hours!

High Temperature Epi:

- Temp up to 2250°C
- growth rates ~ 100 µm/h
- 500 µm in ~ 5 hours or less !
- Halide-assisted, low T growth



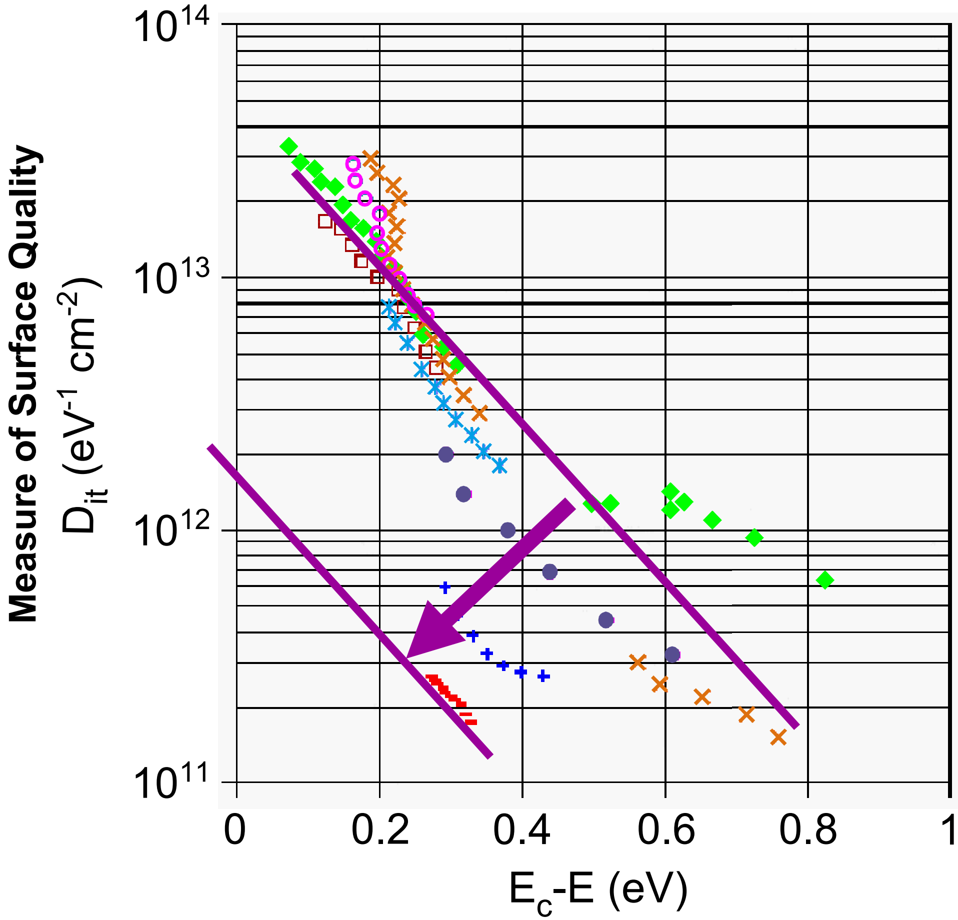
SiC Epi

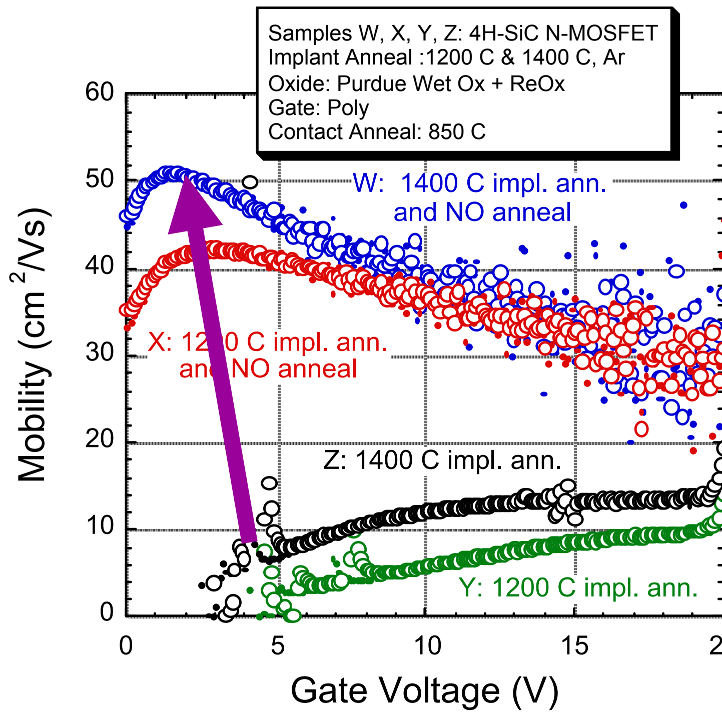
Technical Challenges:

- Component Degradation
- Impurity/Dopant Control
- Morphology & Defects
- Pre-cracking of Precursors

High Temperature Epi Needed for High Growth Rate of WBG

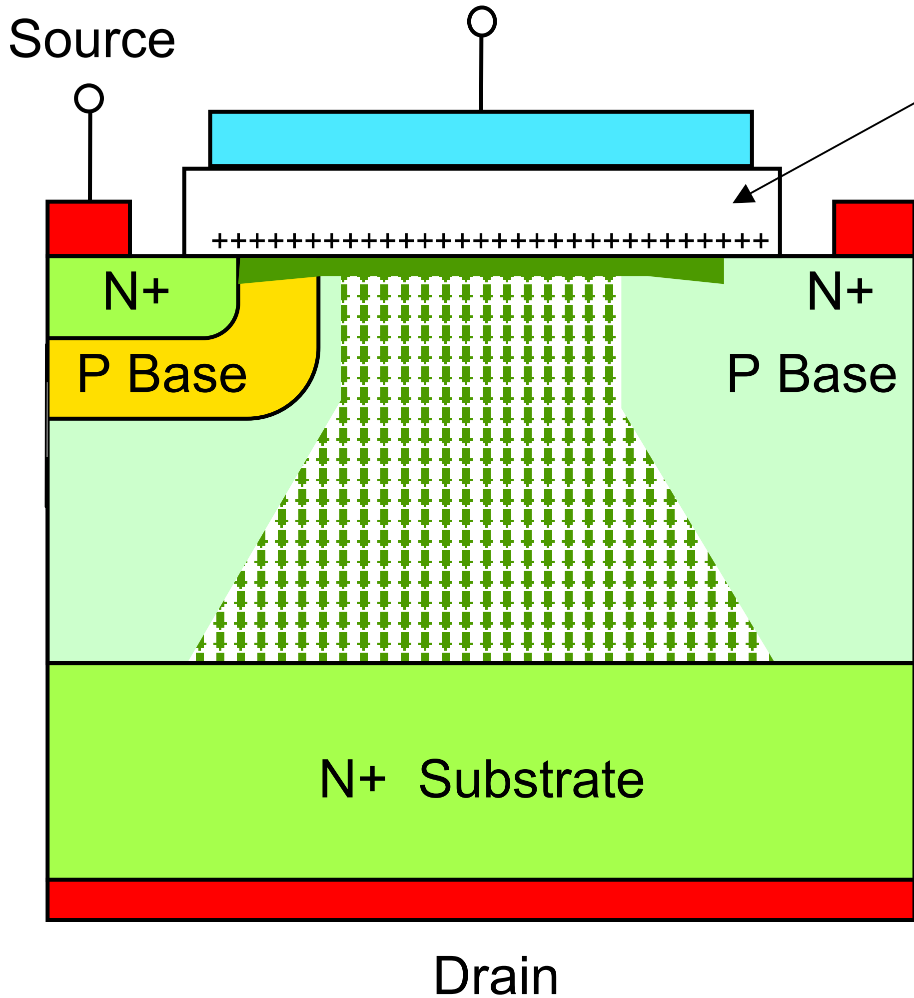
Oxy-Nitride Process Breakthrough for SiC Oxides





Oxy-Nitride Process Proven To Reduce Surface States and Increase Channel Mobility up to 5X to 90cm²/V-s

Ferroelectric Gate Insulators



Lithium Niobate, Lithium Tantalate, Li Gallate have promising properties:

100-1000X inversion charge density

Low field in dielectric

Normally Off

Positive temp. coeff.

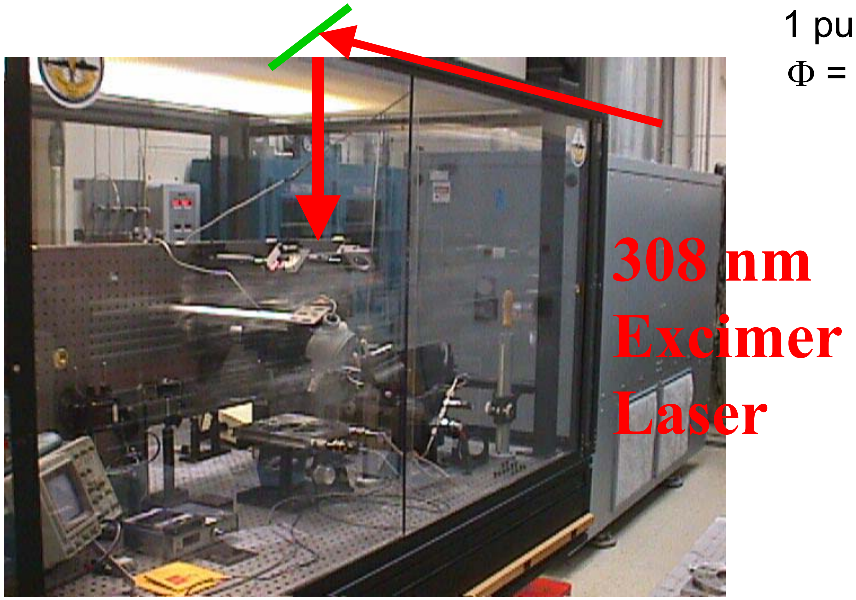
Challenges:

- Growth/deposition with low interface states for high V Temp. stability

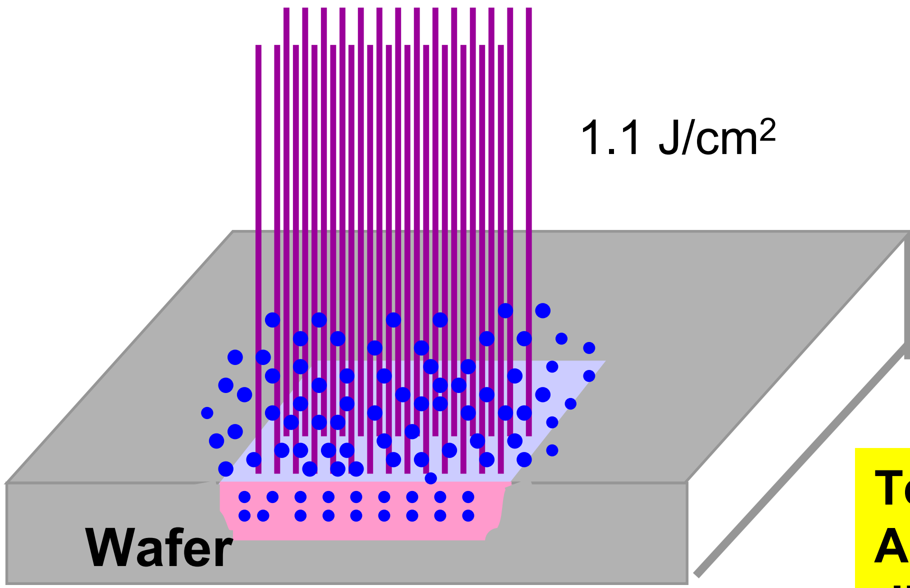
-Breakdown field

High Voltage Ferroelectrics Can Eliminate Thermal Oxides

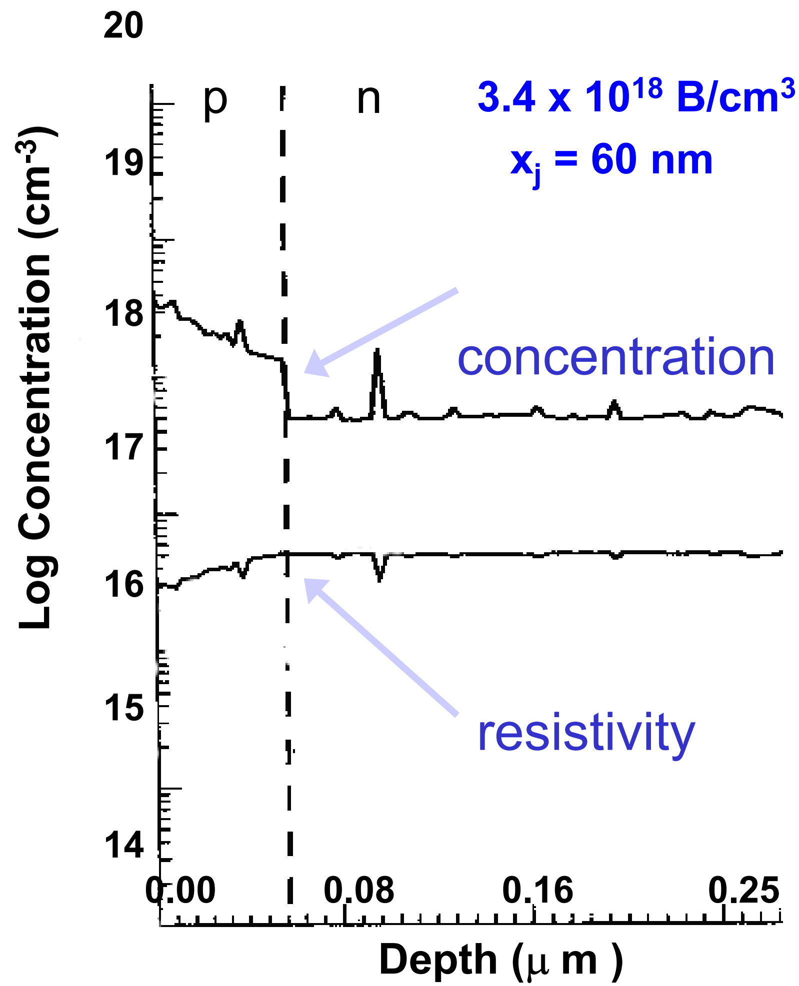
Gas Immersion Laser Doping



1 pulse
Φ =

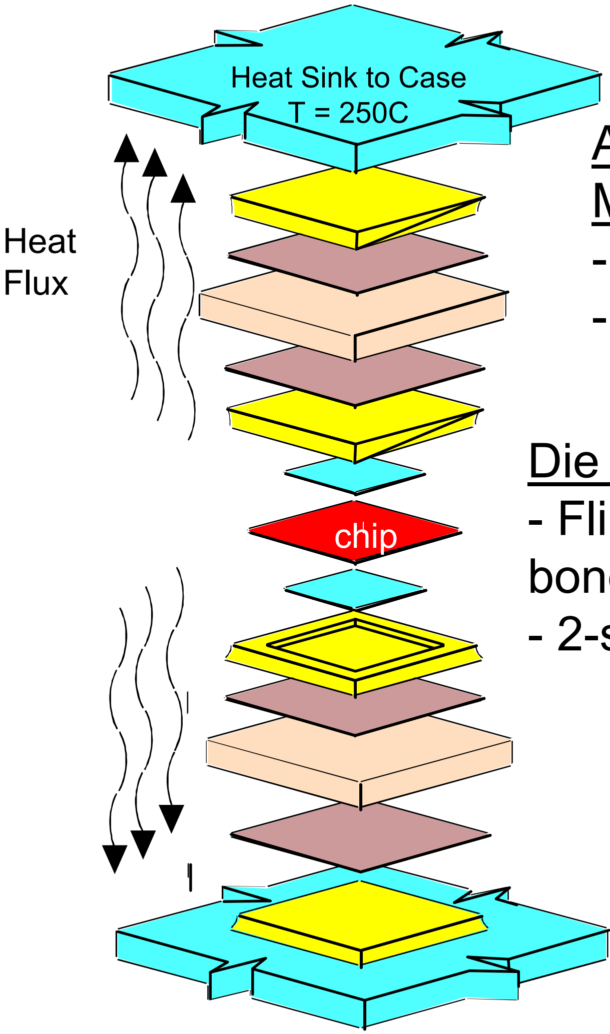


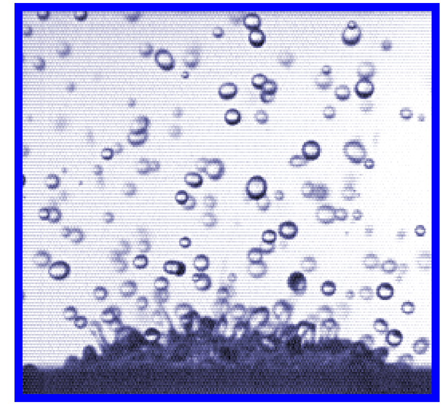
Doping Results



Technology Proven with Silicon FETs – Achieving doping above solid-state diffusion limit using laser processing

Integration for WBG Electronics





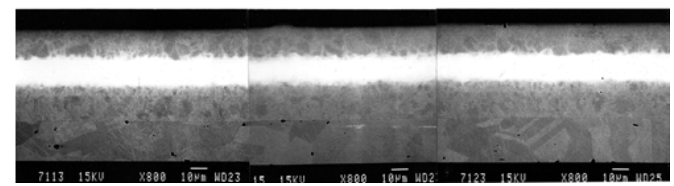
AC and Transient Thermal Management

-Phase change materials

-Integrated spray cooling

Die Attach

- Flip chip via Cu/Sn alloy bonding
- 2-sided cooling

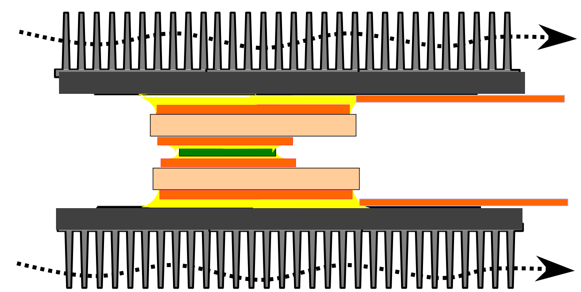


Substrates

-High voltage insulators

-High thermal conductivity

-Low TCE mismatch



Integration and Thermal Management Is Critical for Realizing WBG Device and Circuit Benefits at System Level

Technology Opportunities for R&D in WBG Power Electronics

- Materials and Processes
  - Defect reduction and mitigation
  - Large areas for high current, high voltage
  - Oxides, epi layers, doping activation, mobility, etc.
- Devices
  - MW and beyond switches
  - Novel triggering and commutation
  - Defeat realtime defect growth and propagation issues (minority carrier injection effects)
  - Integrated Structures and Thermal Management
- Applications
  - Compelling!